Surg Endosc (2011) 25:3071–3079
DOI 10.1007/s00464-011-1672-7

Mucoadhesive film for anchoring assistive surgical instruments in endoscopic surgery: in vivo assessment of deployment and attachment

V. Pensabene · P. Valdastri · S. Tognarelli · A. Menciassi · A. Arezzo · P. Dario

Received: 23 August 2010 / Accepted: 4 March 2011 / Published online: 13 April 2011

Abstract
Background Flexible endoscopic procedures in the gastric cavity are usually performed by operative instruments introduced through the working channels of a gastroscope. To enable additional functions and to widen the spectrum of possible surgical procedures, assistive internal surgical instruments (AISI) may be deployed through the esophagus and fixed onto the gastric wall for the entire duration of the procedure. This paper presents a solution for deploying, positioning, and anchoring AISI inside the stomach by exploiting a chemical approach.
Methods A mucoadhesive polymer was synthesized and tested inside the stomach. In vivo trials were performed on a porcine model by introducing the AISI provided with mucoadhesive by means of an overtube through the mouth. Targeted deployment was achieved by a purposely developed delivery device, passed through the operative channel of a gastroscope. The total time for deployment, positioning, and anchoring of the AISI was evaluated by testing the procedure with passive modules (10, 12, 15, 20 mm in diameter) and active devices: e.g., a miniaturized wired camera and a wireless illumination module. The time and force required for the detachment of the modules were measured.
Results The whole procedure of in vivo deployment, positioning, and attachment of an AISI was performed in approximately 6 min. A preload force of 5 N for 3 min was required for anchoring the modules. The stable adhesion was maintained for a maximum of 110 min. Thanks to the positioning of the camera in the fundus, a wide view of the gastric cavity was obtained. The force required to detach the modules reached 2.8 N.
Conclusions Mucoadhesive anchoring represents a completely biocompatible and safe solution for stable positioning of AISI onto mucosal tissue. This novel polymeric mechanism can be useful for designing intraluminal accessories and tools that enhance surgeons' performances in endoluminal procedures.

Keywords Mucoadhesion · Endoluminal surgery · Assistive tools · Anchoring system

Since the introduction of flexible endoscopy in the 1960s, oral access to the gastrointestinal lumen has enabled the examination of the gastric cavity and allowed performance of a wide range of procedures that often are able to replace open surgical techniques and that lead to less invasiveness [1]. Diagnostic endoscopic retrograde cholangiopancreatography and sphincterotomy [2, 3], biliary stent placement [4], and removal of gastric polyps [5] or small superficial gastric malignancies by snare cauterization [6] are some of the most effective endotherapeutic maneuvers currently

V. Pensabene · P. Dario
Istituto Italiano di Tecnologie (IIT),
Center for Micro-BioRobotics IIT@SSSA, Pontedera, Italy

P. Valdastri · S. Tognarelli · A. Menciassi · P. Dario
The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy

A. Arezzo
Centre of Minimally Invasive Surgery,
University of Torino, Turin, Italy

P. Valdastri (✉)
The BioRobotics Institute, Scuola Superiore Sant'Anna Polo Sant'Anna Valdera Viale Rinaldo Piaggio,
34, 56025 Pontedera, Italy
e-mail: pietro@sssup.it
URL: http://www-crim.sssup.it/

performed in the stomach. However, the ability by these procedures to manipulate tissues is limited because of instrument limitations and space confinement [7].

In this framework, two innovative approaches can be identified that enhance surgeons' capabilities and at the same time maintain reduced invasiveness.

The first approach consists of the release of assistive internal surgical instruments (AISI), which can be controlled and manipulated from outside the body for performing or assisting minimal invasive surgery inside human cavities, such as the abdominal cavity. A first example of this approach is given by Cadeddu et al. [8] who showed the use of a magnetically anchored camera system during laparoscopic nephrectomy and appendectomy in two human patients. This camera is an example of Magnetic Anchoring and Guidance Systems (MAGS), which consist of internal surgical instruments that can be controlled by an external handheld magnet and thus do not require a dedicated access port. An advanced system that exploited magnetic fixation and positioning was developed by Lehman et al. [9]. This peritoneum-mounted imaging robot consists of a stationary outer tube measuring 21 mm in diameter, with a rotating inner tube that houses the lens, a camera board, and three micromotors, for a total weight of 75 g. An improved prototype of this robotic camera, measuring 12 mm in diameter, is described by Canes et al. [10] and used for performing several natural orifice transluminal endoscopic surgery (NOTES) procedures. A similar approach is presented by Dominguez et al. [11], who employed extracorporeal permanent magnets to control magnetic forceps. With these internal tools they effectively exposed the surgical field, with no need for extra access ports, thus, completing 40 laparoscopic cholecystectomies with a single-incision laparoscopic surgery (SILS) approach. A magnetic camera system also is reported by Simi et al. [12], where an internal motor is used to finely orient the point of view.

The second innovative approach is represented by innovative robotic systems that can be assembled inside the human body, as recently proposed for endoluminal techniques. An example is given by Harada et al. [13], where a modular and reconfigurable robot is proposed for endoluminal intervention in the gastrointestinal tract. Miniaturized surgical tools, capable of entering the human body through natural orifices or very small incisions, can configure themselves into complex kinematic structures and augment the dexterity of endoluminal interventions.

Considering these aspects, a key issue is the capability to position assistive tools or robotic modules onto the inner wall of the target cavity, to stably anchor small devices (i.e., sensors or additional light sources) or improve the stability of magnetically controlled instruments (i.e., robotic cameras).

The purpose of this work is to present and to validate in vivo conditions a novel chemical instrument-anchoring mechanism that can assist traditional flexible endoscopic procedures. Tognarelli et al. [14] thoroughly analyzed mucoadhesive film properties, selecting the optimized formulation and evaluating ex vivo the performance on excised stomach. The experimental section revealed that an optimal preload condition in terms of force and time must be applied to obtain stable anchoring of the module on the tissue. Moreover, the relationship between weight and dimension of the mucoadhesive mockup for an effective adhesion was provided.

This study particularly targets the gastric cavity, where a slippery environment, rich in mucus, makes anchoring a challenging goal to achieve. Nevertheless, the same principle, once demonstrated, may be applied to other cavities, e.g., the abdomen, by modifying the chemical formulation of the polymer.

Materials and methods

Mucoadhesive film preparation

Mucoadhesive films were prepared by varying the method described previously [15] and following the procedure presented by Tognarelli et al. [14]. Briefly, mucoadhesive hydrogel was prepared by mixing a solution of Carbopol® 971P NF (CP971, Noveon Inc., Cleveland, OH; 1% w/w into deionized water) with three additional water solutions, prepared with Polyvinylpyrrolidone (PVP, 10% w/w), Polypropylene glycol (PPG, 3% w/w), and a nonionic surfactant, Pluronic (PF127, 1% w/w) to reduce the wettability of the film. A few drops of triethanolamine were added to the final clear hydrogel to neutralize the dispersion (pH 6.9–7.2). The dispersion was thus processed under vacuum at room temperature to remove the entrapped air, kept overnight at 4°C to complete hydration, and then poured into polystyrene Petri dishes. Next, the produced samples were dried in an oven at 38°C for 24 h. After demoulding, the films were stored at room temperature for 48 h before use. The film could then be cut into the desired shape and size (Fig. 1). In a previous work [14], the mucoadhesive formulation was tested ex vivo considering the effect of each component. The optimal preload conditions in terms of force and time were defined by performing tests with freshly excised stomach tissue, demonstrating that a preload force of 5 N must be applied on the sample for at least 3 min to ensure intimate contact between the tissue and the mucoadhesive film. The preload value plays a key role in the initial binding between the polymeric film and the mucus and was demonstrated to guarantee stable anchoring of the module in an ex vivo setting.

Fig. 1 Different sizes of prototype passive modules. On the *right*, the mucoadhesive film (final thickness of 0.2 mm) is attached onto the module base

Prototype modules

To assess the proposed anchoring strategy in vivo, cylindrical modules were fabricated by rapid prototyping (ProJet HD3000, 3D SYSTEMS, USA). The mucoadhesive film, once cut with the same base section of each module, can be glued to it using cyanoacrylate (Fig. 1). These mock-ups were fabricated in different diameters, i.e., 10, 12, 15 and 20 mm, mimicking potential AISI modules. In particular, the 10 mm and the 12 mm diameter modules were used to demonstrate the feasibility of endoluminal deployment, whereas the modules all together were used to quantify the influence of the surface area on adhesion performance. Weight variation can be considered negligible, because it varies from 8.82 mN (0.9 g) to 13.72 mN (1.4 g).

In addition to passive mock-ups, two active modules were developed to provide a concrete application for AISI mucoadhesive anchoring. The selected functions were vision and illumination, which were implemented as a wired and as a wireless module, respectively. A VGA camera (Misumi mo-s588, Taiwan), provided with a four light-emitting diodes (LED) illumination system, was accommodated inside a cylindrical module fabricated by rapid prototyping. This active module (Fig. 2A) is provided with a lateral cable for powering and data transmission, and is 12 mm in diameter, 20 mm long, and weights 41.16 mN (4.2 g). A mucoadhesive film, shaped as the cross-section of the module, was glued on the opposite side of the camera lens using cyanoacrylate. The main purpose of this AISI was to provide the surgeon with an additional point of view during the procedure. A second active module was designed for supplying additional light inside the stomach. In this case, four white LEDs, a LiPo Ion battery, and a miniaturized driving board were housed into a cylindrical casing. This AISI (Fig. 2B) is 12 mm in diameter, 25 mm long, and weights 34.3 mN (3.5 g). The module is untethered and the LEDs are switched on by wireless communication.

These active modules can be deployed inside the gastric cavity by means of a delivery device described in the next section, which is compatible with off-the-shelf flexible endoscopes.

Deployment system

The 10 mm and 12 mm diameter modules were introduced into the porcine stomach using a modified version of a commercially available endoscopic delivery device (AdvanCE^{TM}, US Endoscopy), inserted through the working channel of a traditional endoscope. This device was originally designed to deploy the Given Imaging PillCam directly inside the stomach [16], by means of an internal rigid cable pushing the pill out from a distal container as the operator pulls the handle. This system was adapted to deliver mucoadhesive modules by implementing two main modifications. First, two customized distal containers were produced by rapid prototyping to host the 10 mm and 12 mm diameter modules (Fig. 3A). The outer diameter was 11.2 and 15 mm, respectively. The container can be screwed on the distal part of the delivery device, once this has been passed through the operative channel of

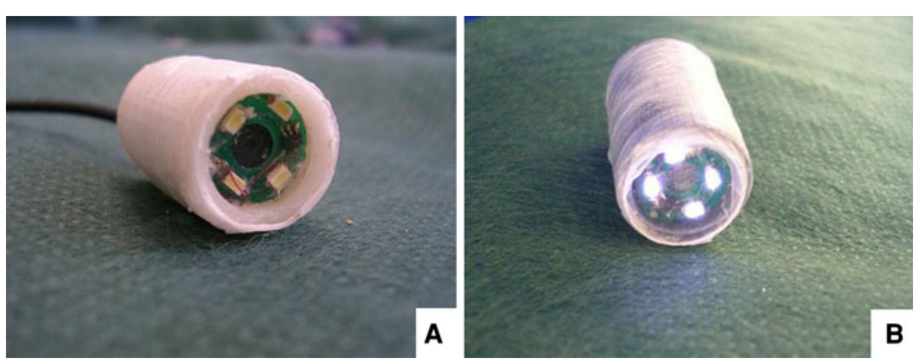

Fig. 2 Different AISI modules provided with mucoadhesive film: (**A**) wired camera module; (**B**) wireless illumination module

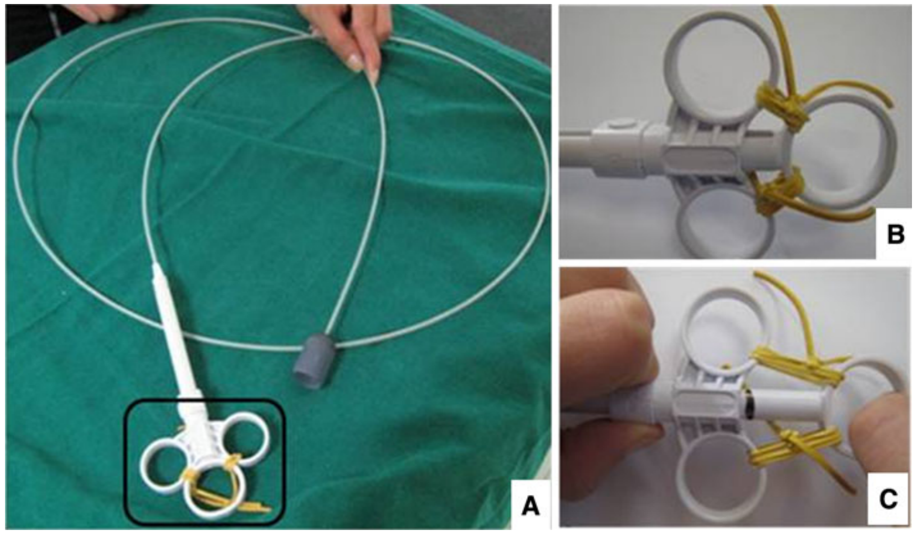

Fig. 3 **A** Delivery device for mucoadhesive modules deployment. **B** Modified handle in resting conditions. **C** Handle pulled to a reference distance to achieve 5 N on the distal part. A *black reference line* indicates the correct handle position

the endoscope. The module was inserted in the container exposing the adhesive tape.

Because mucoadhesive film requires that a preload be applied for a certain time, a second substantial modification was made to the original device, consisting of the addition of two elastic rubber bands (Fig. 3B), which were tied to the handle of the delivery device. This allowed the distance at which the handle was pulled by the operator to be related to the preload force exerted by the inner rigid cable on the module to be deployed on the distal side of the instrument. To obtain an accurate value for the preload force (i.e., 5 N as previously mentioned), the proposed deployment system was calibrated by pushing a mucoadhesive module, placed inside the distal container, against a load cell (ATI NANO 17 F/T, Apex, NC, USA). Thus, the handle was pulled until the force exerted by the module reached 5 N and a reference line was marked on the instrument (Fig. 3C).

In case several modules have to be deployed inside the gastric cavity, an overtube can be used to protect the patient's esophagus from mucosal shearing or tearing and to reduce the time required for multiple scope insertions. In our study, a Guardus Overtube (US Endoscopy, USA) was used. Its inner diameter—17 mm—allowed both the endoscope and the delivery device to be easily inserted.

In vivo validation

In vivo tests were performed on five female pigs (60 kg average weight) to assess the effectiveness of deployment and the anchoring performance of different modules in a real operative scenario. In particular, a first set of tests aimed at deploying 10 mm and 12 mm passive modules in the antrum of the stomach to demonstrate the feasibility of fixing several modules in precise locations. Then, the active modules were attached to the fundus to provide an additional viewpoint of the stomach and adequate illumination. Finally, a dedicated set of trials performed in open conditions quantified the normal force that the mucoadhesive film can withstand, referred as detachment force (F_D), as a function of the module diameter.

All of the animal tests were performed in specialized experimental animal facilities, with the assistance of a trained medical team in compliance with the regulatory issues related to animal experiments. After intravenous

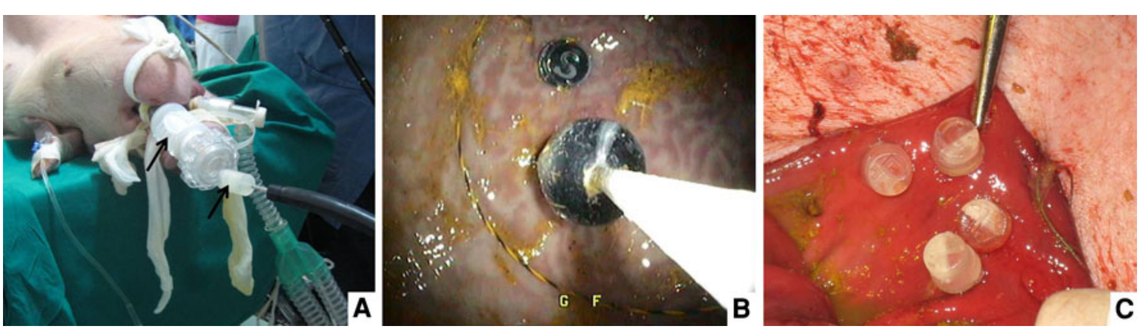

Fig. 4 **A** Deployment procedure, *arrows* highlighting overtube inlet and module container. **b** View of the operative area from the endoscope tip. **c** Four modules deployed endoscopically (necroscopy inspection)

Table 1 F_D and module diameter relationship for mucoadhesive films

Module diameter (mm)	F_D (N)
10	1.94
12	2.33
15	2.6
20	3.85

sedation of the animal, the overtube was introduced down to the stomach through the mouth. Then, the delivery device was installed on the endoscope (STORZ, 13803 PKS, Head V2.4, Germany). A first 12 mm module was loaded into the distal container and then introduced inside the stomach through the overtube (Fig. 4A). Although the container was located in front of the camera, the operative area was always visible (Fig. 4B). Once in the stomach, a location on the antrum was selected for deployment of the first module. A 5 N preload force was exerted for 3 min using the mechanism described in the previous section. The endoscope and the delivery device were retrieved and a second module was loaded in the container. The same procedure was repeated with the goal of placing the second module close to the first one. This was repeated until four modules were attached in a defined area (Fig. 4C). The deployment time, defined as the period ranging from the insertion of the module-loaded deployment system through the mouth to the module release after the proper preloading, was measured together with the adhesion time, defined as the period of time the modules were able to remain attached to the gastric wall. The same procedure was repeated for the deployment of four modules with a diameter of 10 mm. To assess the efficacy of the polymeric film and to clean the modules, they were rinsed with water for 1 min after deployment.

As previously mentioned, the active modules, i.e., the camera and the light source, were deployed in the fundus by following the same procedure. In this case, the time for deployment and the duration of adhesion also were recorded.

At the end of the in vivo session, a set of trials was performed in open conditions to evaluate the mucoadhesive detachment forces in the normal direction alone as a function of the contact area. Cylindrical passive modules with diameters of 10, 12, 15, and 20 mm were placed in contact with the gastric tissue and the preload force (5 N) was applied on each sample for 3 min. A digital load cell (Alluris, FMI210, Germany) with 0.01 N resolution and 0–50 N measuring range was used to apply the preload force and to quantify the normal detachment force. To minimize the deformation of the stomach tissue during the measurements and to correctly apply the preload force, the tissue was held in a constrained position and the normal detachment force was quantified by pulling the load cell in the perpendicular direction. The detachment force was measured immediately after the preload phase. A new mucoadhesive film and a different gastric wall area were used for each trial.

All the measurements described in this section, i.e., deployment time, adhesion time, and detachment force, were performed at least ten times to achieve statistical relevance, and all the data reported in the following section are given as averaged values (with the exception of Table 1, where minimum values are reported).

Results

In vivo validation

All of the operations were completed by deploying the modules by endoscopic route using the delivery device, which assured stable handling and simple release. No case required the need to convert to open surgery.

The preload force was applied by managing the delivery system; 5 N enabled stable anchoring to be achieved for 110 min with the 10 mm modules. The adhesion time of the different modules reached at least 80 min and was not influenced by the position of the modules inside the stomach but can be related to the quantity of mucus and to the weight of the modules (Table 2).

As reported in Fig. 4, the introduction, positioning, and release tasks were completed sequentially. Targeting and release procedures were performed by the endoscopist, who evaluated the desired position under endoscopic vision, and an assistant, who handled and operated the delivery device. Once the target spot was identified, the endoscopist blocked the endoscope tip position and the

Table 2 Summary of modules characteristics (weight and diameter), position inside the gastric cavity and adhesion time

Module	Weight (mN)	Diameter (mm)	Position	Time (min)
Cylindrical modules	8.82	10	Antrum	≈110
Cylindrical modules	10.78	12	Antrum	≈97
Wired camera	41.16	12	Fundus	≈80
Wireless LED module	34.3	12	Fundus	≈95

assistant performed the deployment procedure. This consisted in bringing the container in contact with the lumen and then pulling the handle up to the marked line to exert the desired preload force. The container placed in front of the endoscope did not hamper vision (Fig. 4B), neither during introduction nor gastric wall inspection. The field of view was obviously wider when deploying 10 mm modules rather than 12 mm modules, due to the container's dimensions. The deployment systems can be considered optimal because more than 80% of the attempts were successful. Thanks to the use of the overtube, esophageal tissues were preserved from damages during the introduction procedure.

The average time for completing the introduction, positioning, and anchoring procedure of a single module was approximately 6 min with a very steep learning curve. A group of 12 mm modules deployed in the same area is represented in Fig. 4C.

Rinsing the module for 1 min with fresh water did not affect adhesive film stability, because the surface of the polymer did not come in contact with the liquid and adsorption was avoided. After removal of the modules, when the module came off by itself or when it was removed manually, the gastric mucosa did not show any visible scar (Fig. 5), confirming that adhesion is completely reversible and safe.

The wired camera was positioned in the fundus (Fig. 6A) to provide an auxiliary viewpoint of the surgical field, thereby augmenting vision (Fig. 6B). Time for deployment was 6 min, and the delivery device worked properly despite the curvature of the endoscope. The weight of the camera can be sustained for approximately 1 h and 20 min, and the module can be removed by simply retracting the power cable.

The wireless illumination module was deployed and anchored onto the stomach surface (Fig. 7) with the same procedure in 6 min and 30 s. The wireless system represents a secondary assistive tool that improves the light level inside the operating theater.

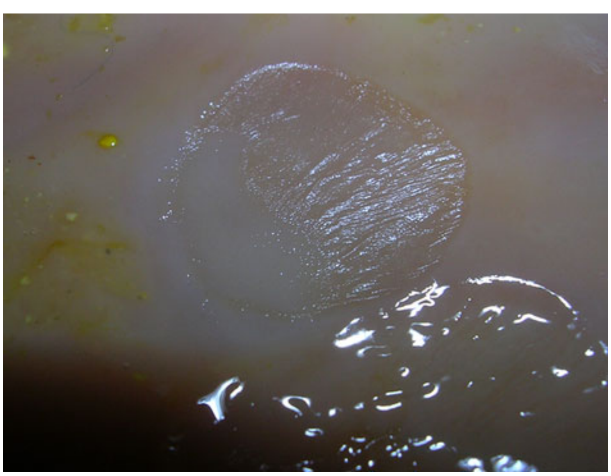

Fig. 5 Gastric mucosa after detachment of the module

The in vivo sessions were concluded in open conditions to quantify the mucoadhesive detachment forces in the normal direction. The preload force (5 N, 3 min) was applied and then the cylindrical passive modules (10, 12, 15, and 20 mm in diameter) were retracted from the gastric mucosa.

As summarized in Table 1, surface area is a fundamental parameter for adhesion of the modules on the tissue. It is worth mentioning that the larger the module diameter, the higher the force required for its detachment from the tissue. This aspect, already investigated in ex vivo trials [14], can be ascribed to the higher level of chemical and physical binding, which can occur if the contact surface is enlarged.

The minimum force required for the detachment of the 10 mm diameter modules was 1.94 N and reached 3.85 N with the larger module, exposing a contact area of $\sim$310 mm^2.

Discussion

Endoluminal surgical procedures access the gastrointestinal tract from natural orifices by means of traditional flexible endoscopes, which provide vision and operative tools. In the case of specific procedures, such as transgastric exploration or difficult polypectomy, free standing and independent assistive tools can be helpful. This is the case of cameras offering additional complementary points of view on the operative area, or sensors that monitor physiological parameters (e.g., tissue ischemia, inflammation, bleeding) or the status of the surgical operation (e.g., intragastric and transmural gastric pressure). All of these functions can be assigned to softly tethered independent tools, which do not require dedicated access, thus leaving the working channel of the endoscope available for active instruments, such as snares or knives.

Therefore, it seemed of great interest to us to investigate and validate a mucoadhesive technology that could anchor AISI tools on the mucus covered gastric walls, test in vivo a procedure for deploying and positioning single modules, and measure the anchoring strategy performance.

The design of the prototypes stems from anatomical constraints and the need to use traditional flexible endoscopes. The 10 mm and 12 mm modules thus represent realistic mock-ups for use in endoluminal surgical interventions. The delivery system proved to be effective for introducing modules through the mouth and positioning tools on a precise target location, without significant reduction in the endoscopic field of view. Thanks to the use

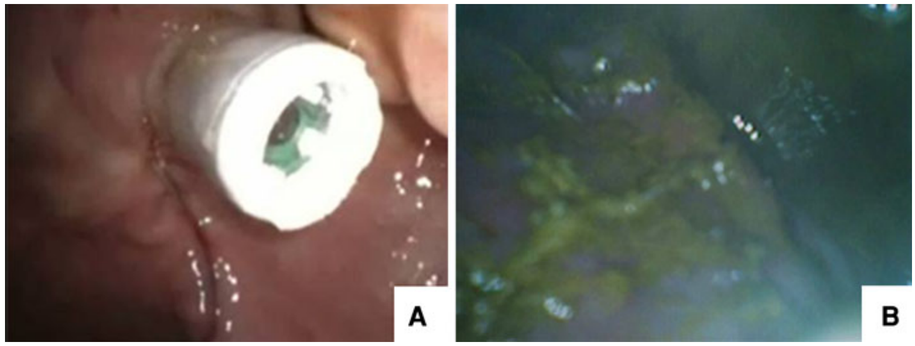

Fig. 6 **A** Wired camera attached on the mucosa. **B** View of the stomach wall obtained from the mucoadherent camera

of a commercial overtube, the deployment procedure can be easily performed multiple times, without causing wounds to the esophageal inner tissue.

The entire procedure, including insertion, preload force application, and release, was performed in approximately 6 min in all cases. Moreover, once deployed and attached on the gastric mucosa, anchoring remained stable for more than 1 h. In addition, the detachment force was measured in vivo, validating the results obtained ex vivo by the authors in [14].

The experiments on a porcine model were performed with "active" and "passive" modules having different diameters. Considering the dimensions, contact surface is a key factor during adhesion, which is governed by chemical and physical factors. Because it is possible to define a linear relationship between contact area and detachment force, the results obtained in vivo with module diameters of 10, 12, 15, and 20 mm can be summarized as follows:

$$F_D = C\, r^2$$

where F_D is the achievable detachment force, r is the radius of the module adhesive surface, and C

Fig. 7 Wireless illumination module anchored on the gastric mucosa

(0.0101 ± 0.002 N/mm^2) is an experimental coefficient relating r to F_D.

Considering this formula as a criterion for the design of an AISI to be deployed and anchored by a mucoadhesive film, material selection and geometry are key issues to minimize weight and maximize the surface of the module in contact with the mucosa. Again, with regard to transoral access, smart anchoring structures that open once inside the gastric cavity can be designed by taking inspiration from umbrella-like mechanisms or stents, to offer a wider contact area. Thus, given the weight of the AISI, the required surface area of the mucoadhesive can be used to guarantee stable adhesion, while still exploiting oral access.

In terms of weight, the modules presented in these experiments range from 8.82 to 41.16 mN and adhesion time decreases in vivo from approximately 2 to 1 h and 20 min with the heaviest module. As regards in vivo adhesion time for "light" weights (below 41.16 mN), it may be predicted on the basis of the polynomial trend found for modules with loads ranging between 147 and 245 mN. Comparing ex vivo and in vivo results, the rapid decrease in the latter case can be attributed to physiological conditions and to the presence of mucus on the tissue. In excise samples the tissue gradually dries, whereas with in vivo conditions the mucosa continually secretes, thus favoring the hydration and swelling of the polymeric film.

As illustrated, the mucoadhesive formulation is conceived with the purpose of accomplishing a reversible attachment on the mucosa, thanks to the dynamic water absorption properties of the polymeric film and its binding with the mucus. However, the swelling behavior of the adhesive film was controlled during the design phase to check resistance to direct streams of water. Mucoadhesive anchored tools can be detached only by exerting a defined value of retraction force, which breaks the physical and chemical binding between film and mucus, without impairing any damage to the tissue. Mucoadhesion represents a completely biocompatible and safe system for the stable positioning of AISI on the gastric mucosa even in the presence of water. Commercial graspers may be used for detaching the anchored modules from the mucosal wall.

Concerning the force–time relation for the polymer adhesion, factors that influence the adhesion and detachment forces were previously evaluated by ex vivo tests [14]. The detachment phase is much shorter than the time of adhesion, thus the detachment event can be modeled, for the sake of the proposed application, as a step transition occurring as the adhesion time is elapsed. This mechanism was properly investigated in ex vivo environment, finding a direct dependence between time of adhesion, contact area, and swelling properties of the polymer. These last two factors are related to the chemical and physical behavior of the polymer, because the larger is the contact area and the higher is the number of active bindings on the polymer surface enabling the adhesion. Moreover, the dynamic uptake of water (i.e., swelling index) regards the anchoring stability of the polymeric system to the gastric mucosa.

In the detachment phenomena in vivo, the results observed ex vivo are confirmed. Omitting the forces due to the movement of the animal and the weight of the module, the established hydrogen bindings between the carboxylic groups of the carbomer contained in the mucoadhesive film and the mucin glycoproteins of the mucus layer are broken while the polymer gradually swells and melt down, finally showing an instantaneous detachment of the module. Future efforts will be devoted to analyze this aspect in details by performing additional tests.

Mucoadhesive AISI could be proposed as supporting tools for metabolic [17] and bariatric [18] surgery. Additionally, other techniques, such as natural orifices transluminal endoscopic surgery (NOTES) [19], may benefit from the use of purposely developed AISI attached to the inner gastric wall. Fundoplication, used in the treatment of gastroesophageal reflux disease (GERD) [20], is another procedure that may take advantage by mucoadhesive AISI. Furthermore, the proposed adhesion strategy can play a fundamental role in endoluminal robotic surgery, where the stable adhesion of the feet of the robot against the stomach wall must be guaranteed [13]. Other devices already reported in literature that might benefit from similar concepts range from deployable pH or obscure bleeding sensors [21, 22] currently anchored to the lumen wall by surgical clips, to physiological transducers that can be used to monitor the status of a tissue during a surgical operation [23]. In this framework, aiming to further reduce the preload time and force, modifications of the chemical formulation are currently under consideration.

This novel polymeric mechanism also may be used to design magnetic modules for tissue retraction by simply embedding a permanent magnet inside the shell. Once attached to the target site, this part of tissue can be moved by an external hand-held permanent magnet, thus allowing a multiaxial traction-countertraction, which could be required to expose hidden areas during gastric exploration. This retraction method also may be used for gathering biopsy samples, thus representing an alternative strategy to magnetic glue [24], which could alter the sample conditions and so the diagnostic outcomes.

A further possible perspective is the local release of specific anti-inflammatory drugs loaded in the polymeric mucoadhesive film, for local treatment of targeted tissues. Finally, it is worth mentioning that the proposed chemical adhesion can be extended and modified in future works to wet mucus-free surfaces, such as the peritoneal cavity, thus widening the impact of this method to abdominal surgery.

Conclusions

Mucoadhesion films guarantee a stable anchoring mechanism for assistive surgical instruments in endoluminal procedures inside the stomach. Thanks to the purposely designed delivery system, the modules can be easily deployed directly onto the mucosal tissue. The obtained results, in terms of force and time of adhesion, pave the way for the definition of novel techniques, where the attachment of one or multiple assistive surgical modules on the wall of the operative area could enhance surgeons' capabilities and improve the outcomes of the procedure.

Acknowledgment Research support for this study was provided by the European Commission in the framework of ARAKNES FP7 European Project 224565.

Disclosures V. Pensabene, P. Valdastri, S. Tognarelli, A. Menciassi, A. Arezzo, and P. Dario have no conflicts of interest or financial ties to disclose.

References

1. Ponsky JL (2006) Endoluminal surgery: past, present and future. Surg Endosc 20:S500–S502
2. McCune WS, Shorb PE, Moscovitz H (1968) Endoscopic cannulation of the ampulla of Vater: a preliminary report. Ann Surg 167:752
3. Kawai K, Akasaka Y, Murakami K, Tada M, Koli Y (1974) Endoscopic sphincterotomy of the ampulla of Vater. Gastrointest Endosc 20:148
4. Huibregtse K, Katon RM, Coene PP, Tytgat GN (1986) Endoscopic palliative treatment in pancreatic cancer. Gastrointest Endosc 32:334
5. Lanza FL, Graham DY, Nelson RS, Godines R, McKechnie JC (1981) Endoscopic upper gastrointestinal polypectomy. Am J Gastroenterol 75:345
6. Randall GM (1992) Endoscopic diagnosis of gastric neoplasms. Gastrointest Endosc Clin North Am 2:469
7. Martınez-Serna T, Filipi CJ (1999) Endoluminal surgery. World J Surg 23:368–377
8. Cadeddu J, Fernandez R, Desai M, Bergs R, Tracy C, Tang SJ, Rao P, Desai M, Scott D (2009) Novel magnetically guided intra-abdominal camera to facilitate laparoendoscopic single-site surgery: initial human experience. Surg Endosc 23:1894–1899

9. Lehman AC, Berg KA, Dumpert J, Wood NA, Visty AQ, Rentschler ME, Platt SR, Farritor SM, Oleynikov D (2008) Surgery with cooperative robots. Comput Aided Surg 13:95–105
10. Canes D, Lehman AC, Farritor SM, Oleynikov D, Desai MM (2009) The future of NOTES instrumentation: flexible robotics and in vivo minirobots. J Endourol 23:787–792
11. Dominguez G, Durand L, De Rosa J, Danguise E, Arozamena C, Ferraina PA (2009) Retraction and triangulation with neodymium magnetic forceps for single-port laparoscopic cholecystectomy. Surg Endosc 23:1660–1666
12. Simi M, Ciuti G, Tognarelli S, Valdastri P, Menciassi A, Dario P (2010) Magnetic link design for a robotic laparoscopic camera. J Appl Phys 107(9):09B302–09B303
13. Harada K, Oetomo D, Susilo E, Menciassi A, Daney D, Merlet JP, Dario P (2010) A reconfigurable modular robotic endoluminal surgical system: vision and preliminary results. Robotica 28(2): 171–183
14. Tognarelli S, Pensabene V, Condino S, Valdastri P, Menciassi A, Arezzo A, Dario P (2011) A pilot study on a new anchoring mechanism for surgical applications based on mucoadhesives. Minim Invasiv Ther 20:3–13
15. Dodou D, Breedveld P, Wieringa PA (2006) Stick, unstick, restick sticky films in the colon. Minim Invasiv Ther 15(5): 286–295
16. www.givenimaging.com
17. Schulman AP, del Genio F, Sinha N, Rubino F (2009) “Metabolic” surgery for treatment of type 2 diabetes mellitus. Endocr Pract 15(6):624–631
18. Blackburn GL, Mun EC (2005) Therapy insight: weight-loss surgery and major cardiovascular risk factor. Nat Clin Pract Cardiovasc Med 2:585–591
19. Kobiela J, Stefaniak T, Mackowiak M, Lachinski AJ, Sledzinski Z (2008) NOTES-third generation surgery: vain hopes or the reality of tomorrow? Langenbecks Arch Surg 393:405–411
20. Pleskow D, Rothstein R, Haber G, Gostout C, Lo S, Hawes R, Lembo A (2008) Endoscopic full-thickness placation for the treatment of GERD: five-year long-term multicenter results. Surg Endosc 22:326–332
21. Kwiatek MA, Pandolfino JE (2008) The Bravo (TM) pH capsule system. Dig Liver Dis 40(3):156–160
22. Schostek S, Müller V, Rieber F, Ho CN, Rakoschi C, Anhoeck G, Schurr MO (2008) Implantable optical sensor concept for the detection of gastrointestinal bleeding. Conference of the society for medical innovation and technology, SMIT 2008
23. Errachid A, Ivorra A, Aguilo J, Villa R, Zine N, Bausells J (2001) New technology for multi-sensor silicon needles for biomedical applications. Sens Actuators B 78:279–284
24. Wang Z, Wang L, Tang B, Frank T, Brown S, Cuschieri A (2008) Retraction by surface ferromagnetisation of target tissues: Preliminary studies on feasibility of magnetic retraction for endoscopic surgery. Surg Endosc 22:1838–1844